THE INFLUENCE OF MATERIAL ELECTROMAGNETIC PROPERTIES TO THE ELECTRIC MOTOR PERFORMANCE

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Abstract

With the electrification of the road vehicles in recent years, the development of electric motors strives towards smaller and more efficient designs. In order to push forward the current limits of the electric and magnetic properties, e.g. magnetic saturation of the ferromagnetic parts in the motor, novel materials must be developed. In this paper, the comparison of different materials, i.e. C45 steel, FeSi and FeCo alloys, which are used in the rotor magnetic structure of an electrically excited synchronous motor, is presented. Regarding the electic and magnetic properties, each of the materials is a representative of its own material family. The materials were evaluated by measuring their electrical conductivity and static B-H curve. It is shown by the 2D finite elemet method analysis that the materials with elevated magnetic properties allow improvements in the electric motor design, leading to the enhanced performance, which is reflected in lower energy consumption (higher efficiency) and/or lower mass (higher compactness).

Keywords: Iron-cobalt alloys, FeCo, electromagnetic properties, performance, electric motor

1. INTRODUCTION

In comparison to standard silicon steels (FeSi), which are commonly used for building the magnetic cores in the electric motor manufacutring, iron-cobalt (FeCo) alloys offer significant performance improvement due to lower magnetic field strength H, needed to magnetize the material, and higher saturation flux density B_{sat} values, which is reflected in more compact geometry, higher energy efficiency and mechanical power [1-5].

Magnetic cores are normally constructed of laser-cut or stamped laminations in order to reduce the core losses, originating from the time-varying magnetic field. FeCo alloys have been used as laminated cores in the high performance permanent magnet electric motors, e.g. Formula SAE [6,7], where the increase of the efficiency and torque within the same motor dimensions has been demonstrated.

On the other hand, using a non-laminated magnetic core would be possible only when the magnetic field is constant, e.g. in the rotor of an electrically excited synchronous motor (EESM) [8, 9]. Apart from the magnetic core, such rotor contains also an excitation winding as the other active part, which is supplied with direct current (DC) that excites constant magnetic field. Rotor pole shoes (**Figure 2**), located at the air gap, must be from laminated material to avoid parasitic losses due to stator slotting and higher harmonic components in the air-gap magnetic field.

The focus of this paper is to analyze the influence of FeSi and FeCo ferromagnetic material properties on the EESM performance, particularly the losses and efficiency for overload and nominal operation. The performance improvement has been demonstrated via 2D transient finite element method simulations for overload and nominal operation. Thus, the potential of the die-cast (massive) FeCo material usage in EESM design has been presented.

2. MATERIAL PROPERTIES

Batches of 10 kg alloys were melted in a vacuum induction melting furnace with an Al_2O_3 crucible. The Fe-Co-V and Fe-Si-Al were melted and vacuumed for 20 minutes under 5 Pa. Pure elements electrolytic Al, Co, Fe, Si and V were used to produce the desired alloys. The alloys were cast into a two part mould to produce a 400 mm long rectangular ingot with 60 mm x 60 mm cross section. The as-cast samples were cut and the rest of the ingot was hot rolled at 1100 °C to 20 mm thickness.

Apart from the aforementioned FeSi, i.e. standard material with up to 3 % of silicon for reducing the electrical conductivity and consequently the eddy current losses, and FeCo – die-cast advanced magnetic material with equal share of Fe and Co, the C45 steel, which is commonly used material for electric motor shaft, was also analyzed in this study. All material samples were round rods with 10 mm in diameter and 100 mm in length (**Figure 1b**). Each sample was die-cast, cut and machined to these dimensions. Magnetic properties were measured by the MagnetPhysik Remagraph [10], which measures static magnetic B-H hysteresis loop (**Figure 1a**). The essential electric and magnetic material data are gathered in **Table 1**, where they are compared with the reference materials [11,12]. FeCo shows superior magnetic properties compared to FeSi and C45, i.e. lower magnetic field strength for magnetization and higher saturation magnetic flux density, which can be graphically seen also in **Figure 1a**.

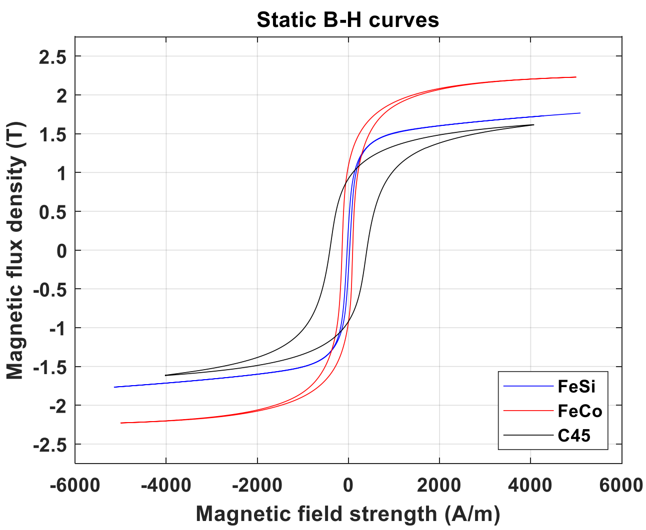

Figure 1 a) Measured static B-H hysteresis curves of the analyzed materials; b) material samples

Table 1 Electric and magnetic properties of the analyzed materials

Material	Electrical conducivity at room temperature (MS/m)	Magnetic field strength at B = 1.6 T (A/m)	Saturation level at H = 4000 A/m (T)
M270-35A [11]	1.92	3,880	1.61
VACUFLUX 50 [12]	2.38	< 300	2.26
FeSi	2.36	2,000	1.72
FeCo	2.44	642	2.17
C45	4.44	4,000	1.60

Another important aspect in the electromagnetic energy conversion are the specific losses of the material. They consist of hysteresis and eddy current losses (1). The former depend on the material properties, reflected in the surface area of B-H hysteresis (**Figure 1a**), and frequency (2), while the latter depend on electrical conductivity, thickness, magnetic flux density and frequency (3). Assuming that the materials are rolled into sheets with the thickness of 0.35 mm, the calculated values for FeSi and FeCo specific losses are given in **Table 2**, where they are compared with the values of the reference materials, i.e. FeSi is compared with M270-35A [11] and FeCo with VACUFLUX 50 [12].

$$p = p_{hys} + p_{ec} \tag{1}$$

$$p_{hys} = A_{BH} f \tag{2}$$

$$p_{ec} = \frac{\sigma d^2 \pi^2}{6} B^2 f^2 \tag{3}$$

where:

A_{BH} - surface area of B-H hysteresis (J/kg)
σ - electrical conductivity (S/m)
d - lamination thickness (m)
B - magnetic flux density (T)
f - electrical frequency (Hz)

Table 2 Calculated specific losses (W/kg) at different frequencies at 1.5 T and 400 Hz

Material	**Hysteresis losses (W/kg)**	**Eddy current losses (W/kg)**	**Total losses (W/kg)**
M270-35A [11]			41.8
FeSi	8.6	21.9	30.5
VACUFLUX 50 [12]			31.0
FeCo	54.8	21.7	76.5

As it can be seen in **Table 2**, the hysteresis losses of the produced FeCo alloy are much higher than the FeSi, leading to higher total losses, which can be observed also in the surface area of the hysteresis loops in **Figure 1a**. In order to produce technically more competitive alloy, which could be used also as lamination sheets for the electric motor parts, where the time-varying (AC) magnetic fields are present, e.g. stator core, the area of the hysteresis loop must be significantly reduced.

3. ELECTRIC MOTOR PERFORMANCE

The influence of the material electromagnetic properties on the electric motor performance was analyzed on the benchmark electric motor geometry of the Renault Zoe electric vehicle. It is an AC synchronous electric motor with electrically excited rotor (**Figure 2**), meaning that its structure is conceptually identical to the low-speed synchronous generators in power plants. The DC current in the rotor winding magnetizes the motor with the magnetic field, which in interaction with stator AC winding produces torque and mechanical power.

All magnetic parts of the electric motor must be laminated, apart from the main part of the rotor magnetic structure, which may be die-cast due to the DC rotor magnetic field. This simplifies the production of the rotor core and offers opportunities for performance improvement by using advanced ferromagnetic materials, e.g. FeCo alloys. Namely, these alloys have higher values of magnetic saturation and consequently the cross section of the rotor magnetic core can be reduced for the same amount of magnetic flux to be transferred through it. Narrower rotor magnetic core increases the area, available for the rotor excitation winding, leading to lower losses in it. This is then reflected into increased energy efficiency of the electric motor and easier heat removal from the rotor.

The calculations were performed in Altair Flux 2D software, with the imposed rotor speed and current fed stator winding. The stator and rotor winding resistance values, used in the simulation, were obtained by the measurements on the benchmark motor.

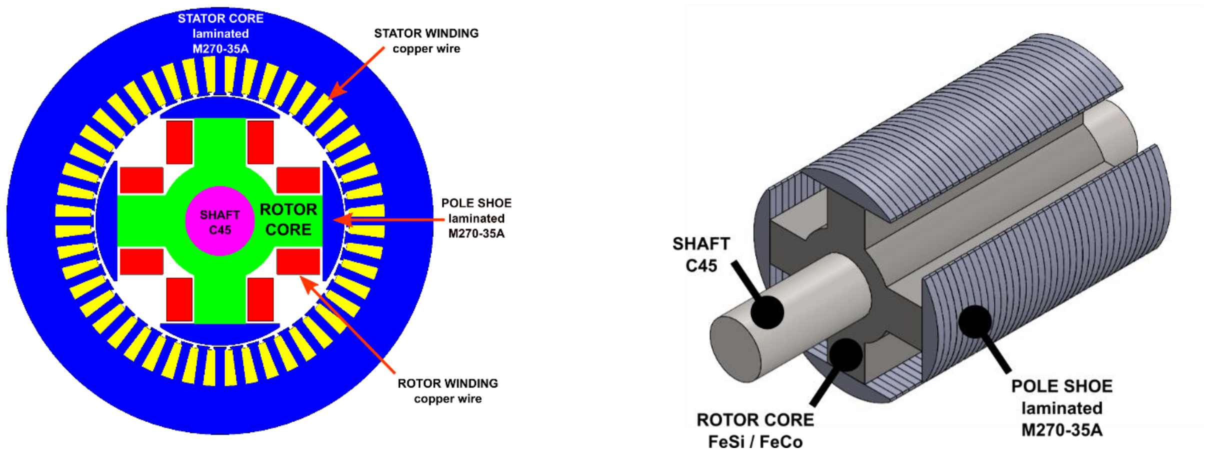

Figure 2 a) benchmark electric motor geometry (2D electromagnetic model), b) rotor magnetic design (3D model)

Two operating points of the benchmark motor are of interest. The first one is the maximum mechanical power of 80 kW delivered to the shaft, i.e. at 225 Nm and 3400 min^{-1} of shaft torque and rotor speed, respecitvely, with the supplying electrical frequency of 113.3 Hz. The second one is the continous mechanical power of 20 kW (56 Nm, 3400 min^{-1}). Energy efficiency in both operating points is calculated by using (4). The caluclated values for different rotor core materials are given in **Tables 3** and **4** for maximum (80 kW) and continuous power (20 kW), respectively.

$$\eta = \frac{P_{mech}}{P_{mech} + P_{loss}} \qquad (4)$$

where:

η - energy efficiency (-)

P_{mech} - mechanical power (W)

P_{loss} - total losses (W)

Table 3 Electromagnetic efficiency at maximum power 80 kW

Rotor core material	**Stator losses**	**Rotor losses**	**Energy efficiency**
FeSi	P_{stator} = 14.534 kW	P_{rotor} = 3.194 kW	81.9 %
FeCo	P_{stator} = 12.859 kW	P_{rotor} = 3.194 kW	83.3 %

Table 4 Electromagnetic efficiency at continuous power 20 kW

Rotor core material	**Stator losses**	**Rotor losses**	**Energy efficiency**
FeSi	P_{stator} = 1.323 kW	P_{rotor} = 422 W	92.0 %
FeCo	P_{stator} = 1,063 kW	P_{rotor} = 423 W	93.1 %

4. CONCLUSION

The analysis, presented in the paper, showed a significant performance improvement of an electrically excited synchronous motor in terms of energy efficiency, when the iron-cobalt alloy is used in the rotor magnetic structure. Smaller magnetic field strength is needed for the magnetization of the motor, leading to the smaller magnetization current and consequently smaller rotor losses. The energy efficiency could be further improved by narrowing the rotor poles due to higher values of saturation magnetic flux density of iron-cobalt alloy, leaving more room for the rotor excitation winding. Consequently, the cross section area of the excitation winding is increased, thus further reducing the Joule losses for the same level of overall motor magnetization.

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